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Artificial production of precipitation

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1. Introduction.

Cloud consists of small water drops or ice crystals, or a mixture of both. It is a matter of observation that cloud droplets can continue to exist in liquid form at temperatures far below 0°C, to -20°C or even lower. Water cloud at temperature lower than 0°C is said to be supercooled.

Typical cloud particles are so minute - much smaller than typical raindrops or snowflakes - that they remain in suspension: or, if they fall from the cloud, evaporate completely before reaching the ground.

The occurrence of rainfall or snowfall, as normally understood, implies the operation of processes within cloud which result in growth or aggregation of cloud particles to drops or snowflakes which, by reason of their size and increased rates of fall, reach the ground before evaporation is complete.

Attempts to produce precipitation by artificial means must aim to assist or stimulate natural processes.

2. Outline of natural precipitation processes.

Most precipitation in substantial amount (other than drizzle) falls from cloud several thousands of feet in vertical extent.

The release of natural precipitation from cloud is attributed to two main processes, one of which depends on the presence of ice crystals in cloud.

(a) Rôle of ice crystals.

In temperate latitudes, at least, the temperature of the upper parts of the majority of precipitating clouds is as low as -12°C, or lower. Natural ice crystals are found to occur in the supercooled parts of cloud, and more probably and more profusely at temperatures of about -10°C and lower.

When ice crystals and supercooled water droplets co-exist the crystals grow at the expense of the neighbouring droplets which therefore decrease in size or vanish. The optimum temperature for this stage of growth is between -10° and -15°C. The larger crystals fall relatively to the smaller liquid or solid cloud particles. Further growth by collision with other crystals and supercooled droplets results in the formation of crystal aggregates, i.e. snowflakes, of sufficient size to reach the ground as snow, or as rain if they melt in the warmer lower parts of cloud or in the air below. It has been suggested that the splintering of ice crystals during the process of growth gives rise to additional crystal elements and so to additional snowflakes (or, eventually, rain drops).

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On occasions, well-developed cumulus ('shower') clouds with tops at temperatures below -12°C do not precipitate. It has been claimed that this is due to the lack of natural ice crystals in the upper parts of the clouds.

(b) Coalescence of droplets.

Particularly, though not exclusively, in tropical areas substantial rainfall occurs from well-developed cloud no part of which is at a temperature below 0°C. There is no question of the ice crystal process in such conditions. As the growth of a cloud droplet to a raindrop by condensation alone is a very slow process, the rain must result primarily from the coalescence of water droplets. Cloud droplets are not of uniform size. Droplets larger than normal, when carried upwards and downwards by the air currents within the cloud, grow by sweeping up a proportion of smaller droplets and eventually become large enough in vertically deep cloud to fall out as rain. Some may grow sufficiently to split up into a number of drops large enough to initiate further cycles of growth by coalescence. There is evidence that hygroscopic elements (having affinity for water) such as sea spray are carried up into clouds and constitute the relatively large droplets which are the first stage in the coalescence mechanism.

The coalescence process doubtless operates also in deep clouds which extend upwards to temperatures below 0°C (as in (a) above).

3. Artificial rain-making.

(a) General.

The possibility of producing rain, or snow, by human intervention is by no means a new concept, though it is only since 1946 that rather intensive and widespread effort has been devoted to the problem. In 1946 research staff of the General Electric Company of America demonstrated in the laboratory that an artificially produced cloud of water droplets at a temperature well below 0°C changed very rapidly to a cloud of minute ice crystals after the introduction of a particle or two of solid carbon-dioxide (dry ice) of which the temperature is in the neighbourhood of -70 to -80°C. Ensuing experiments, by the G.E.C. group, in which pellets of dry ice were dropped from aircraft into natural supercooled cloud showed that changes of cloud structure occurred and that snow fell from the cloud in a short time after the 'seeding' operation. These early results aroused much interest and were quickly followed by similar experiments and related investigations in America and several other countries. Much of the subsequent work has been investigational in character and carried out by official or comparable institituions. There has also been considerable commercial exploitation, notably by American agencies.

At an early stage it became evident that it is possible in favourable conditions to induce rain or snow to fall from certain clouds by seeding them with dry ice. As mentioned below, other methods of cloud seeding have been suggested. The effectiveness of present methods of attempting to produce precipitation in conditions which would be unlikely to give rise to natural precipitation, and the significance of the amount of precipitation produced artificially are still controversial topics.

Other proposals or speculations which have emerged relate to the application of cloud seeding to prevent hailstorms and the more intense downpours of rain, and also to the possibility of clearing low cloud e.g. in the vicinity of airfields.

(b) Methods of cloud seeding.

The chief methods which have been used in recent years are outlined briefly below.

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(i) Dry ice.

Pellets of dry ice are dropped from an aircraft into water-drop cloud of which the top at least is at temperature some degrees below 0°C. The likelihood of success is greater if the cloud-top temperature is lower than -7°C.

Intense local cooling produced in the cloud along the paths of the falling pellets of dry ice results in the formation of numbers of minute ordinary ice crystals, which become diffused by turbulence within the cloud. Subsequent growth of the crystals to the magnitude of precipitation elements may be expected, as outlined in para. 2(a), in favourable conditions.

From the remarks in para. 2(a) on the rôle of naturally occurring ice crystals in water cloud at temperature lower than -12°C, in initiating natural precipitation, it would appear that the utility of seeding with dry ice is restricted mainly to occasions or stages of cloud development where the tops of cloud are at temperatures between -7°C and -12°C. Hence, it is argued, the injection of dry ice at the appropriate stage of growth (judged by temperature at the top) should result in precipitation falling earlier than, and in a different area from, precipitation which would result from further development of the cloud.

Dry ice evaporates quickly in falling to levels of higher temperature.

(ii) Silver iodide.

When introduced into supercooled water cloud at a temperature lower than -3 or -4°C, extremely small crystals of silver iodide lead to the formation of ice crystals. The ice crystals may form, not as a result of intense cooling as is produced by dry ice, but because the crystalline structure of silver iodide and ice are closely alike and the minute silver iodide crystals serve as nuclei for the formation of ice crystals. The effectiveness of silver iodide as a producer of ice crystals appears to increase rapidly as temperature decreases from -3° or -4°C to -15°C but thereafter changes little.

Ice crystals produced in cloud through the agency of silver iodide may be supposed, in favourable circumstances, to grow by natural processes and result in precipitation from the cloud, as indicated in para. 2(a). If the quantity of silver iodide used in seeding results in the production of too numerous elementary ice crystals in relation to the number of water droplets present, the ice crystals will not grow sufficiently to initiate precipitation, but the supercooled water cloud will be transformed to a cloud of small ice crystals.

In seeding operations, the silver iodide in finely divided form is produced by vaporising a solution of silver iodide in acetone containing an alkali iodide. The vapour can be injected directly into cloud at the appropriate temperature by means of apparatus carried on aircraft; or, somewhat less directly, by means of small bombs, containing gunpowder impregnated with silver iodide, carried upward into the cloud by small balloons and arranged to explode sufficiently high above the 0°C level. Much of the cloud seeding with silver iodide has been done with generators suitably deployed at ground level, a procedure less costly than any involving the use of aircraft. The invisible effluent from a generator travels with the wind, diffusing as it goes and, if upward air currents are present, enters cloud and eventually may reach the temperature levels at which silver iodide is effective in ice crystal formation.

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It would appear that there must be some uncertainty as to when or whether silver iodide generated at the ground will reach the right part of the cloud, or even the right cloud mass, but advocates of the method claim that proper positioning of generators in relation to the area on which it is desired to produce precipitation can be achieved by making due allowance for changes of wind direction and speed with height (say to 15,000 feet above ground) and other local conditions.

Silver iodide does not dissolve in water, evaporate or melt. It may therefore be long-lived in the atmosphere and might conceivably affect cloud remote from the area of operations. There is however some uncertainty as to the effectiveness of this substance after exposure to sunlight.

(iii) Water drops.

Water drops of diameter about 1/20 to 1/10 millimetre have been sprayed by aircraft into the lower parts of cloud some thousands of feet in vertical extent and in which there is updraft. Drops of the size mentioned are larger than the majority of cloud droplets: the aim of the method is to promote the coalescence mechanism referred to in para. 2(b).

(iv) Hygroscopic material.

Very fine particles of a hygroscopic substance quickly become relatively large liquid droplets when introduced into a cloud of water droplets and, if the cloud conditions are suitable, would be expected to cause precipitation by the coalescence process indicated in para. 2(b).

Trials have been made by dispersing a mixture of finely powdered sea-salt and calcium chloride (hygroscopic substances) in the lower part of suitable clouds. The material and a charge of gunpowder are carried up by a small balloon into the cloud and arrangements made for the charge to explode at an appropriate height above the cloud base.

(c) Discussion.

From the outline of the bases and the methods of attempts to cause precipitation artificially we pass to a review of the evidence on results.

Assessment is by no means a straightforward matter. A particular cloud may be seen to yield rain or snow at from 10 to 40 minutes after it has been treated with dry ice, but it is often difficult or impossible to be certain that precipitation would not have fallen naturally from that cloud at about the same time or somewhat later. In a series of well controlled experiments carried out jointly by the U.S. Air Force, National Advisory Committee for Aeronautics and the U.S. Weather Bureau in March - September 1948 (ref. 1), precipitation fell from 18 cumulus-type clouds after seeding with dry ice when there was no precipitation before seeding, but in all except five of the cases natural precipitation occurred within a radius of 30 miles and even in these five cases natural showers were occurring within 40 to 60 miles. On the other hand, seeding of suitable cumulus-type cloud with dry ice by the Radio Research Division of the Commonwealth Scientific and Industrial Research Organisation (C.S.I.R.O.), Australia, during a three-year period resulted in rain falling from the cloud on about 100 occasions when similar (unseeded) cloud in the immediate neighbourhood produced no rain. Observations of results were made visually and by radar. Information as to the amounts of rain which reached the ground on these occasions is less precise because of absence of rain gauges in the paths of some of the showers, but it is stated that estimated amounts of rainfall ranged from 0 to 0.25 inch.

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At this point, in relation to amount of rainfall, it may be noted that even if a cloud 30,000 feet in vertical extent and of average constitution were to deposit its entire content of liquid water the resulting rainfall would be about one-fifth inch in the area affected, unless there were some mechanism for replenishing the cloud. The heavier falls of rain which occur naturally are associated with systems in which natural forces maintain renewal of the cloud as the water is precipitated. There is no evidence that methods of cloud seeding mentioned earlier can induce mechanism which results in the replenishment of a particular precipitating cloud. Indeed many of the operations aimed to produce precipitation for utilitarian purposes have been restricted to occasions on which a suitable cloud system is maintained for sufficiently long periods of time by natural processes.

Although some qualitative estimation of the results, positive or negative, of the seeding of clouds may be obtained by visual and radar observation (and probably more readily when the seeding agent is injected from an aircraft than when silver iodide is diffused from ground generators), information more quantitative in character is required in assessing the efficacy of cloud seeding in causing precipitation. It is not sufficient merely to compare the amount of rainfall measured at places in the 'target' area on a day of seeding operations with the amount of rainfall received on the same day at places in neighbouring similar areas ('control' areas) which could not have been affected by the seeding operations. While it is true that there is normally an 'average' relationship between the natural rainfall received at two places not too far apart and subject to the same general regime of weather there can be on occasions substantial departures from the normal 'average' relationship. This random natural variability is found not only in the rainfall received in the course of a day but also in the rainfall for a month or longer period. Therefore, the difference in rainfall in the target area and a control area on days of seeding operations must be compared with the range of natural variability in the difference between the areas on non-seeding occasions. It is desirable when practicable to determine the natural variability of rainfall difference between the two areas from rainfall measurements made in each during as many years as possible before the advent of seeding. If, from such statistical processes, it is concluded that there is a high probability that the difference between the rainfall amounts in the target and control areas on occasions of seeding is greater than is to be expected from natural variability, the effects of seeding on those particular occasions are regarded as statistically significant. It has been represented that it is not valid, when determining the standard ('average') relationship between natural rainfall in a target and a control area, to group all rainfall amounts together irrespective of the weather situations in which they occurred; in other words, that separate target-control area relationships should be determined for a series of different types of rain-giving weather situations and that the significance of the relationship between target and control area rainfalls on occasions of seeding should be assessed against the standard relationships for the types of weather situation in which seeding was carried out. This proposed refinement, which is an indication of the complications encountered in measures to evaluate the results of cloud-seeding, raises the question of how closely the weather situation on a seeding occasion might resemble any of the types selected as standard.

From this background of generalities we proceed briefly to note some published accounts of rain-making operations and experiments.

Africa

The Overseas Food Corporation in collaboration with the East African Meteorological Department conducted experiments during the rainy season January - April in 1951 and 1952 (2,3). The site of the experiments was a cleared area of some 200 square miles near Kongwa, Tanganyika. There was a network of about 50 raingauges in the cleared area. In the 1951 season the seeding agent used was silver iodide, dispersed either from

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ground generators or from balloon-borne bombs (see para. 3(b)(ii)). There were periods in this season when conditions were unsuitable for successful seeding operations. Considering only days other than these it was concluded that the experiments were probably unsuccessful on 12, inconclusive on 10 and probably successful on 5 days. In the 1952 season ground generators were not used. All seedings were made by balloon-bomb and were conducted in three-day cycles: silver iodide, hygroscopic material (see para. 3(b)(iv)), no seeding, on days 1, 2, 3 and so on. Every care was taken to ensure that the seeding agent should enter cloud above a small region in the central section of the experimental site and be dispersed at the appropriate level in the cloud according to the agent used. Winds were almost entirely easterly. Total amounts of rain for each of the three groups of days, measured in each of the 50 raingauges, were examined. As compared with the distribution of rain on days of no seeding, the rain on days of silver iodide seeding showed an excess in the sector of the site upwind of the central area of seeding, while the central sector showed a definite deficit and the downwind sector no pronounced difference. Rain amounts for the group of days of hygroscopic seeding showed an excess upwind, a marked deficit over the central sector but a pronounced excess in the extreme downwind part of the downwind sector. The report mentions the possibility that the apparent deficit of rain in the central area of seeding with silver iodide and in the downwind sector was due to overseeding with the material, but regards the apparent enhancement of rainfall in the extreme of the downwind sector on days of hygroscopic seeding as consistent with the time interval which would be expected for rain to develop following that method of seeding. Further careful similar experiments are desirable.

America

Results of seeding operations by the California Electric Power Company in the Bishop Creek part of the Sierra Nevada watershed in 1948 (33 days), 1949 (29 days) and 1950 (19 days) are discussed in a joint report by T.J. Henderson and S.A. Cundiff of the Power Company and Ferguson Hall of the U.S. Weather Bureau (4). Deep orographic cloud before and after the passage of storm systems was seeded, mainly with dry ice though silver iodide was dispensed from the aircraft on a few occasions. Seeding was confined to the Bishop Creek area (about 15 by 5 to 10 miles in extent). Numerical data on the river flow in Bishop Creek and in neighbouring creeks in each of the years of seeding were examined in relation to corresponding data for earlier periods of 20 to 30 years, in the general manner mentioned above. Only for one period, October 1948 - September 1949, was the Bishop Creek river flow significantly greater than expectation. A corresponding assessment of the water content of the snowpack in April of each year in the Bishop Creek and nearby unseeded areas suggested somewhat negative effects of seeding on snowpack. The report states that it is not possible to determine by purely statistical process if the rather pronounced departure of the 1948-9 river flow, from the standard relationship, resulted from the seeding operations or was due to natural causes, but comments that the 1948-9 winter was characterised in the Californian area by pronounced meteorological anomalies which possibly may have been at least partly responsible for departures in relationships between the flows of Bishop Creek and adjacent streams.

Cloud-seeding operations were conducted during the months January to April 1951 over a 10,000 square mile area in Central Arizona by the Salt River Valley Water Users' Association. P.B. MacCready, Jr., of the California Institute of Technology, reported (5) that for each of the four months the proportion of rainfall to normal (average) was greater in the seeded region than in the neighbouring comparison regions and that in relation to corresponding measurements in five and nine previous years (of no seeding) the relative increase in rainfall in the seeded region was statistically significant. G.W. Brier and I. Enger, of the U.S. Weather Bureau (6), found that while the 1951 January - April total rainfall in the seeded region was larger than expected when judged in relation to

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the data for 30 years in the seeded and the comparison regions, the excess could not be rated as significant. On using rainfall measurements from a larger number of stations in the seeded and comparison regions but for a shorter period of 10 years they found the excess of 1951 (January - April) rainfall in the seeded region to be highly significant. These different results, arising from the use of different lengths of comparison records and different selections of rainfall stations, further illustrate the difficulty of assessing the effect of cloud seeding on rainfall.

Commercial cloud-seeding was carried out in the South Oregon Cascades during the months November to March 1949-50 and 1950-51 with the object of increasing the snow pack, and in the Tri-Counties area of Oregon during the months September to June 1950-51 and 1951-52 with the object of increasing precipitation for the benefit of wheat growers. In the Cascades operation the seeding agents used were dry ice, silver iodide and an unknown material, in the Tri-Counties operation silver iodide from ground generators alone was employed. The results of statistical assessment (on the lines indicated earlier) of both Oregon operations have been reported (7) by R.T. Beaumont of the Oregon Agricultural Experiment Station, Medford. For the winter-months operations in the Cascades the criterion used was the relationship between the accumulated water content in snow pack on April 1 (i.e. at the end of each of the two seeding seasons) in the seeded area and adjacent comparison areas as compared with corresponding data during periods of from nine to nineteen earlier years (no seeding). The analysis showed that during the two seasons of seeding there was significantly less water stored as snow on the target area than might have been expected under normal climatic conditions. In dealing with the Tri-Counties operations, November to June, the monthly and total amounts of rain in the target and control areas were examined statistically in relation to corresponding data for 20 years of no seeding. It was found that the relationship between rainfall in the seeded and control areas in the two periods of seeding did not depart significantly from the regression estimates based on 20 years' data, and hence that departures (positive or negative) in the seeding periods may have been due entirely to chance. It should be mentioned that the control area adopted in assessing the Tri-Counties operation, though up-wind of the target area, is subject to a somewhat different climatological régime. The sensitivity of the statistical tests may therefore have been somewhat reduced, but the selection of the particular area was necessitated by the fact that more appropriate areas nearer to the target area were known or believed to be the scene of other cloud-seeding work.

On behalf of the Bonneville Power Administration the Water Resources Development Corporation, Denver, carried out a cloud-seeding programme in the Pend Oreille River Basin, N.W. Montana during 21-30 September 1951. Other seeding projects in Montana or neighbouring states were in operation in September, and also in August and October. This work is the subject of a published report (8) by an independent committee consisting of the chairman of the Power Administration and representatives of the Bureau of Reclamation, the Geological Survey and the Weather Bureau. Statistical evaluation was made of precipitation and stream-flow measurements in the seeded area and unseeded areas during the months of seeding and in the same months in a series of years in which no seeding occurred. The precipitation in the period of cloud seeding in 1951 was found to be within the limits of natural variation while the excess of run-off (stream-flow) was significant only in September. On the basis of the analyses made, and in view of the possibility of effects from other seeding activities, the committee decided that a definite conclusion could not be reached that the seeding operation was effective in increasing the run-off in the river basin. In any event, even in ideal conditions, one ten-day period of seeding would be insufficient to justify firm conclusions.

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From the preceding paragraphs it is a reasonable inference that the American work there discussed yields no clear evidence that cloud-seeding is effective in increasing the amount of rain. This inference is at variance with widely publicised claims from other sources. Very few detailed reports on operations for which unambiguous success is claimed have been available for examination by the present writer and it is possible here to remark only on the results made public and discussed by one commercial organisation. Irving P. Krick, a leading exponent and practitioner of cloud-seeding, in 1949-50 established the American Institute of Aerological Research and the Water Resources Development Corporation, Denver, to undertake work in this field. A 35-page record of a statement by Krick in April 1951 before sub-committees of the U.S. Senate, published in the official report (9), gives much information on the operational organisation and methods of the Corporation and refers to several occasions when cloud-seeding operations in different parts of the United States are considered to have succeeded. Some of these occasions have also been reported separately, and in rather more detail, elsewhere. The Corporation's operations depend on the use of silver iodide emitted from ground generators positioned according to local circumstances and the weather situation at the time. Current weather developments are closely studied and seeding effort is directed specially to weather systems which are most likely to yield rain naturally. One instance presented in reference (9) relates to the seeding of persistent clouds in winter 1950 over the high mountain areas of Colorado with the object to build up snowpack and so to provide storage water for irrigation in the lower plateau region in later months. On December 15, after seedings during six weeks, the water content of the snowpack in the seeded region was 7.6 inches as compared with the normal value of 7.9 inches on February 1: the absolute maximum value at the centre of the operational area is said to have been 250 per cent. of normal as against 25 per cent. of normal in areas to the south and unaffected by seeding. In (10) I.P. Krick and T.B. Smith assess operations conducted between July and December 1950 in northeast New Mexico (2 months), southeast Colorado (two months) and Oregon (3 months). For each of the seven monthly periods the rainfall measured in the seeded region was compared with the amount which would be expected from statistical relationships between rainfall in the seeded and neighbouring control region during periods of from 23 to 37 years. On this basis, the rainfall in the target region was in excess of expectation in six of the seven months, markedly so in two months. The statistical significance of the positive departures in the six months in relation to occurrences of past years was not investigated, on the grounds that reliable techniques were not available. Claims of success in other operations are presented by Krick in (11). Charts are given of the distribution of rainfall (as percentages of the appropriate average amounts for the month) in and up to about 150 miles around a seeded area of about 1,600 square miles in the Horse Heaven Hills district of the state of Washington for the periods June 6 - 8 and June 11 - 12, 1950. A storm system traversed the district during each of the two seeding periods. The normal (average) monthly rainfall for June in the target area is stated to be about 0.5 inch. The distribution chart for each of the two periods shows a compact pattern with rainfall a maximum of about 200 per cent. of the normal monthly amount at or near the target and decreasing outwards from the centre (rapidly, in some directions) to 50 per cent. or less of normal. Elsewhere (in (9)) it is stated that at one station in the area of seeding the rainfall for June 1950 considerably exceeded the largest amount recorded in June during the previous 36 years. The author states that the distribution pattern is so compact and decisive that it eliminates almost entirely the possibility of occurrence by chance. It may be remarked, however, that not dis-similar patterns do occur on some occasions of localized heavy natural rain, though it may be unusual for two occasions to affect a given locality at an interval of four or five days. In the same paper (11) Krick advocates the use of weather analogues in assessing the results of cloud-seeding a storm system. That is, the amount of rainfall measured in the target area in a particular storm system is to be compared with that measured in the same area during a closely similar storm system

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(unseeded) selected from past records, or possibly with the average rainfall of several such similar storm systems. He applies this to the seeding of a particular type of storm during a 6-day period of June 1951 in southwest Nebraska. The average storm of the type in question is said to give rain about equal to the average of all rainfall (for the season) in the area. An individual type analogue (unseeded) in six days of June 1948 gave about 180 per cent. of the average rain and the seeded storm of June 1951 nearly 400 per cent. The author concludes that a good portion of this increment in the June 1951 storm must be credited to the effectiveness of the cloud-seeding operation. The author recognises that the perfect analogue to a given weather system probably cannot be found, but it must be remarked that this method of assessing the results of cloud-seeding will not inspire confidence unless full information is made available on the variability of rainfall amounts associated with a sufficiently large number of storms classified as closely alike. Krick has published (in (12) and the appendix to (9)) a short account of operations undertaken in the Colorado Rockies in the winter months of 1950-51 with the object of increasing the snowpack in the upper watershed of the Arkansas River and others. As it was not feasible to compare the water content of snowpack in the seeded area at dates in the late winter with corresponding snowpack data in closely neighbouring unseeded areas, comparison was made with the precipitation measured during winter months at a position upwind of and some 2,000 to 3,000 feet lower than the area of seeding. Reasonably close correlation had been found between the winter precipitation at this position and the snowpack data in the upper Arkansas Basin during the 11 preceding winters. According to the figures in the paper, the snowpack content in the seeded area in February, March, April 1951 was greater proportionately to the value of precipitation in the upwind control position than in the majority of the 11 preceding years, while the total precipitation at the control position in the seeding period was greater than in the same group of months in all except very few of the 11 previous years. While one may agree with the author that these relationships are suggestive of the effectiveness of cloud-seeding, one could wish that it had been possible to present information on the natural variability of the precipitation and snowpack data over a longer period of years. Krick has stated in (9) and (11) that his organisation has no evidence that cloud-seeding with silver iodide can exercise effect on weather at great distances from the operational area.

Under Project Cirrus, which was operated by G.E.C. of America under the sponsorship of the U.S. Signal Corps and Office of Naval Research, regular seedings, at intervals of a week, of silver iodide from a generator at a site in New Mexico were initiated early in December 1949 and maintained, with some changes in programme, until early July 1951. Towards the end of 1950 and during 1951 Irving Langmuir of G.E.C. announced, (13), (14), that from the earliest stage of the periodic seedings a seven-day periodicity in rainfall had developed, and had persisted, over a large area many hundreds of miles northeastward of New Mexico: and moreover that a similar periodicity in upper air temperature over large areas and the strength of the south-north component of the air circulation across the head of the Gulf of Mexico had been found. Various meteorologists in America, e.g. in (15) and (16), criticised Langmuir's deductions on periodicity in weather elements on the ground that his periodicity was no more significant in the statistical sense than 7-day periodicities which have occurred naturally from time to time in weather elements in previous years before the introduction of cloud-seeding operations. Although this complicated question of the reality of large-scale effects attributed to seeding has been further and extensively investigated by Langmuir (17) and the U.S. Weather Bureau (18), it is believed that the difference of opinion or interpretation persists. Langmuir does not suggest that long-distance and wide-area effects on weather which he describes were caused by direct action of silver iodide more than a thousand miles from the point of release, but rather that some of the silver iodide perhaps drifted eastwards from New Mexico towards the Mississippi region, caused widespread showers there in moister, cloudier conditions and that the latent heat so released was responsible in some way for promoting the

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periodic development of 'storm' circulations which, travelling north or northeast, gave rise to the periodic fluctuations in weather in the northeast of U.S.A. It may be noted that even if the attribution of weather fluctuations of 7-day period in many areas of the country to 7-day seedings in New Mexico were shown to be unwarranted, it would not necessarily follow that seeding with silver iodide is non-effective in causing rainfall in the immediate area of release of the material.

Australia

Mention has been made in the early part of para. 3(c) of the results obtained by C.S.I.R.O., Australia in experiments to seed suitable cloud in the Sydney area with dry ice. It is estimated that suitable opportunities for rain making in that area occur about 30 times a year, though with marked variations from year to year. Suitable meteorological conditions for rain making attempts are discussed in (19). Full quantitative information on the rainfall measured on occasions of seeding appears not to be available. From some 20 or 30 experiments in which silver iodide was dispensed, within cloud, from aircraft it was concluded that this agent, applied in this way, is probably less effective than dry ice (20). The possibilities of rain making by means of silver iodide emitted from a ground generator were examined in July to September 1951 in an area 500 miles west of Sydney in which prevailing winds are very persistent in direction. The rain measured during the period in the downwind quadrant (of a circle of 50 miles radius centred at the generator) slightly exceeded that in the other quadrants but the magnitude of the excess was less than the normal variability between the rainfall measured in the quadrants. C.S.I.R.O. have also experimented (20), (21) with the spraying of suitable cumulus-type clouds with water droplets (see para. 3(b)(iii)). In 10 experiments out of 11, distinct changes in the cloud followed the injection of water spray, while precipitation fell from the treated cloud in eight of the cases but reached the ground in only four. No other clouds in the vicinity produced precipitation for at least two hours after an experiment.

Other countries

Some reports of cloud-seeding in other countries are available (e.g., Canada, France, India, Israel, South Africa and United Kingdom), but are not considered to contain information which adds materially to that given in this memorandum.

4. Conclusions.

Though there may be differences of scientific opinion as to the exact physical mechanism by which dry ice and silver iodide, when introduced into supercooled cloud, lead to the formation of ice crystals in the cloud, it is accepted that dry ice and, perhaps less certainly, silver iodide can initiate precipitation from suitable supercooled cloud in favourable circumstances. With either agent, only the slightest precipitation (if any) is to be expected if the treated cloud is unsubstantial and unlikely to yield precipitation naturally: the main result (if any) would be the dissipation of the cloud.

There is evidence, less extensive, that spraying fine water drops of suitable size into cumulus cloud of sufficient vertical depth will cause showers to fall from the cloud. There is also some published evidence, slighter as yet, that the introduction of finely ground hygroscopic substances into cumulus cloud of sufficient vertical extent may be effective in promoting rain. On current ideas these last two methods, if confirmed, would have special application to cloud at temperatures higher than 0°C and therefore to rain-making attempts in the warmer regions of the world.

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The crucial issue is whether the seeding of cloud over or about to traverse a given locality results in more precipitation on that locality than would have occurred in the absence of seeding. A rigorously absolutely certain answer to this question is unlikely. For the present, any considered and unbiased answer must depend on assessment of probability by critical examination of accurate and adequate factual date. The reports of seeding experiments and operations summarised in para. 3 are believed to be reasonably representative of the general situation and indicate some of the difficulties which beset the assessment of the effects of cloud seeding. The statistical comparison method necessary in judging the effects of a sustained series of seeding operations on precipitation, snowpack or riverflow involves consideration of the natural variability of these items as between the area of operations and neighbouring areas of similar climate - and this is a problem in itself. It is noted in para. 3 that the period of years and the density of observational data used in these comparisons can materially affect the answer obtained. It is not unlikely that in some of the investigations quoted the observational data used were insufficient or otherwise inadequate for the purpose, perhaps unavoidably.

The first four paragraphs on American work in para. 3 refer to area seeding operations mainly extending through periods of months and, in two instances, in more than one year. Considered together, the results of the investigations afford little, if any, certain support to the view that the operations were effective in increasing the amount of precipitation. The two seasons' work in East Africa and the three months' trial of area seeding by silver iodide in Australia yielded no clear evidence of the effectiveness of seeding. The fifth paragraph on American work quotes several results reported by Krick and, with one exception, put forward as evidence of clearly positive effects of seeding. Only one of these reports by Krick is presented in the statistical form directly comparable with that adopted in the other four American reports mentioned, and it shows that in six of the seven months of seeding operations considered the amount of rainfall in the area of operations exceeded the probable amount of natural rainfall to be expected on the basis of statistical relationships between rainfall in the operational and comparison areas in past years. It does not appear possible, from the information available, to reach a conclusion as to the reason for the difference between Krick's results and those which emerged from the four other American investigations mentioned. One may speculate as to the relative effectiveness of the techniques of seeding employed by the different operators. It may be that on some occasions seeding inhibits rather than promotes precipitation and that the relative incidence of these opposed effects in different series of operations may explain in part the differences in the results obtained. Some methods used in assessment of the effects of seeding seem less reliable than others. Some claims of successes achieved in rain-making attempts require to be supported by more detailed information before they can be regarded as convincing. There is need for further experiments or operations, carefully planned and controlled; and, not least important, objectively assessed.

The discussion of the reported results considered does not lead to a definite unqualified answer to the main question. This position may be changed as further information becomes available. It seems at present that cloud seeding may result in some increase in precipitation on some occasions, but there is uncertainty as to the magnitude of the effect and as to the dependability of the method on a given occasion.

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